Analysis of a Combined System of a Earth-Heat-Exchanger and a Heat Pump

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This paper presents an analysis of the system technology of an earth-heat-exchanger combined to a heat pump, which was (ca. 1995 - 2002) realised at the building of the Umwelt-Campus in Birkenfeld, which belongs to the University of Applied Sciences Trier in Germany. The heat pump works for a recovery of the stored heat in a massive absorber at the air-outlet, in order to minimise energy losses in the atmosphere. Examinations and comparisons to others up to now realised earth-heat-exchanger projects in Germany, done by Jörn Herz for reaching his diploma degree, show, that the special configuration at the Umwelt-Campus Birkenfeld seems to be the first of that kind. This presentation gives an overview of the system technology and working principle. Measurements and mathematical modelling were done, in order to evaluate the efficiency of this combined system and to identify to advantages and disadvantages of this realisation. Additional, practical experiences with stability and working conditions etc., made by Andreas Doll, the responsible technical engineer for the Campus Buildings, are integrated.

1. Umwelt-Campus Birkenfeld

The buildings of the Umwelt-Campus in Birkenfeld (UCB) were formerly a military hospital of the US Army in Germany, in the department of Rheinland-Pfalz. In 1993, it was decided to use these buildings to built up a modern University of Applied Sciences. The leading motivation of this university has to be "sustainability". The buildings were completely renovated and extended, consequently regarding technical standards of solar architecture, rational energy management and renewable energy supply systems.

Figure 1: Solar Architecture UCB

In October 1996, the University started with five study courses. Meanwhile, there are two environmental faculties, "Planning / Technology" and "Business Management / Law", with diploma courses in 'Mechanical Engineering', 'Industrial Process Engineering', 'Environmental Planning', 'Applied Informatics', 'Environmental Economics and Business Management' and 'Business and Environmental Law'.

Figure 2: Buildings of the Umwelt-Campus Birkenfeld

Two new accredited master courses (M.Sc.) start in October 2004, "Material Flow Management" in English and "Energy- and Environmental Engineering" in German", both curricula are regularly for two years to reach the degree "Master of Science".

2. Building Technology and Motivation

The buildings of the Umwelt-Campus are supplied completely with renewable energies, with a various amount of converters combined with equipments for rational energy usage like photovoltaic systems, solar collectors, heat pumps, air conditioning, solar architecture, earth-heat-exchanger etc. and a biomass energy conversion plant nearby for heat and electricity. All these technical active and passive converter are integrated in the building automation. The whole system has still to be analysed and optimised. For this reason, it is advantageous to integrate these necessary work on this system in the study courses to teach students, with the possibility of students own real experiences. In a first step, project and diploma works are started, to give an overview of the single system technologies and the technical data together with the underlying physical theories. An important support for this purpose is the deeper inside and knowledge of the technical engineer Mr. Andreas Doll, who is responsible for the whole building system. His experiences and reports given to the students are very valuable. The next step would be optimisations and integration of new technologies for research and development.

One of the first works for diploma thesis is that of Jörn Herz, who analysed the earth-heat-exchanger, which is combined to a heat pump and massive absorber. The earth can be used as a solar heat storage, which can in winter as well as in summer be used for an air-preconditioning. The heat exchanger system consist of horizontal pipes under the earth surface, which guides the air from outside in the building, with a cooling effect in summer and heating in winter. The earth is therefore used as a seasonal heat storage.

Additionally, there is a heat recovery system implemented, which restores a part of the heat of the air leaving the building back to the earth. A massive absorber at the air outlet works as heat storage for a heat pump.

Aim of the diploma thesis of Mr. Herz was first to describe the installed earth heat exchange system at the Campus and the corresponding physical foundations. And second he made measurements and model calculations, to get information about the quality of this installation.

3. System Technology

The technical planning of the system was done by a group of engineering companies, named *Rittgen* [1](Fachbereich Heizung, Sanitär, Lüftung) and *Becker* [2](Fachbereich Elektrotechnik). Supervisor was the Staatsbauamt (LBB[3]) Trier.

The earth heat exchanger starts his function in the year 2000, but today the measurement system is already not completely installed.

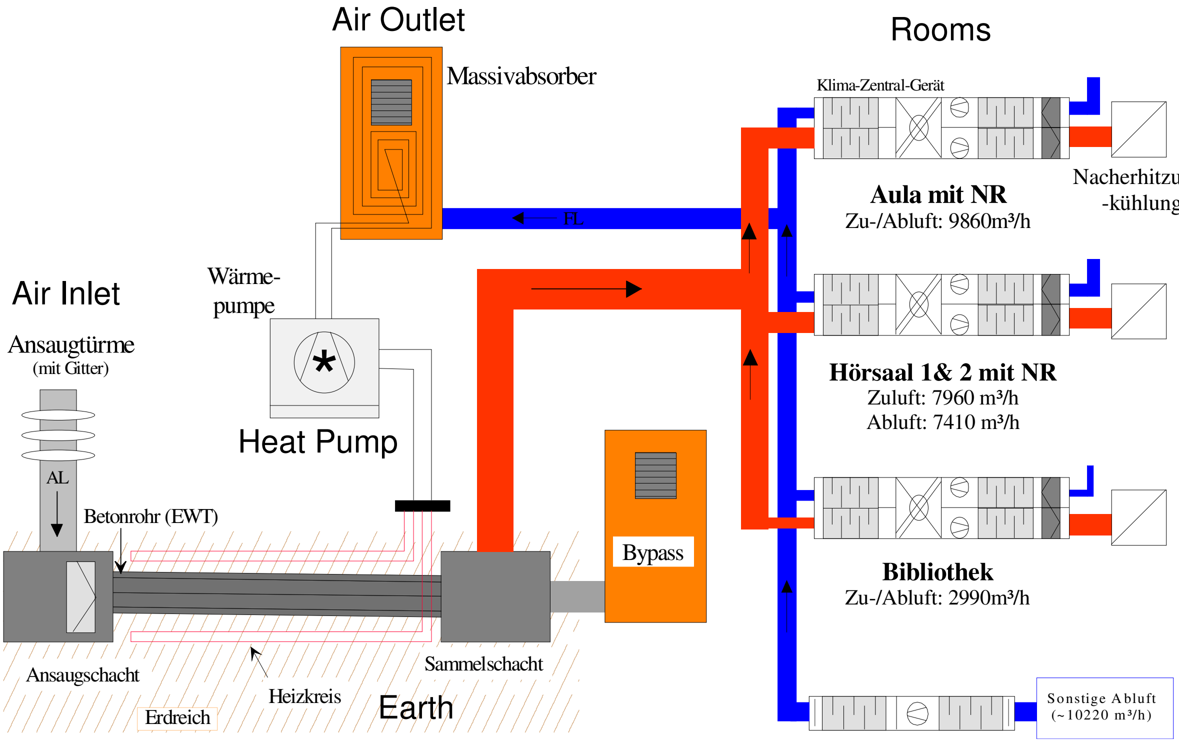

Figure 3: Scheme of the system of the Earth Heat Exchanger with Heat Recovery

The air flow from outside is 15 m³/(h·m²), or 20-30 m³/(h·Person). The dimensioning foundation for this are the rules in [DIN1946], which defines the higher flow of both calculation possibilities. The single flows are given in figure 3.

[1] Ingenieurbüro Josef Rittgen, Am Weidengraben 7, 54292 Trier
[2] Ingenieurbüro Klaus Becker, Herzogenbuscher Straße 1, 54292 Trier
[3] Landesamt Liegenschafts- und Baubetreuung

The air in and out volume flow can be regulated by frequency controlled ventilators with a pressure sensor signal. The air conditioning systems have momentarily to be started manually in the rooms.

An additional CO_2-Monitoring System controls the air inlet stream between the two 80% and 100% ventilator power level. In order to keep the noise level under the limit of 40 dB in the lecture rooms, sound damper were installed. Finally the fresh air has to be cleaned with a fine dust filter of class F7.

The installed heat recovery system at the Umwelt-Campus, with the help of a 14kW electrical heat pump, guarantees a gap free and continuous working condition in winter. The pipes for the recovery heat exchange were mounted symmetrically parallel to the earth heat exchanger concrete air pipes.

The heat pump has fixed working hours and works continuously from 07:00 to 19:00 a clock during the lecture times and variable working times for special courses, seminars, workshops etc. at weekend. This kind of control is to be preferred because of the slow time dependence of the heat exchange processes. As a result of experiences, the earth around the air pipes needs approximately three days to get a stationary temperature load after a cooling down period. The intermittent heat exchange process and the distances in the pipe circuit are arguments against a temperature controlled working condition for the heat pump.

The buildings of the Campus are provided with a complex sensor, measurement and actor system for the automation system, which supervises and controls with a central DDC[4] all parameters, equipments and functions. All pumps, valves, drivers, louvers and adjusting flap valves temperature and are time dependent controlled with a software, and most of the process data are to be stored and evaluated. For this, all over the building there are microprocessor controlled units (PCU´s[5]), wich are interconnected for communication via a LAN bus system.

Additional to the sensors for the building control, the earth for the heat storage and both concrete air pipes have 48 PT100[6] sensors (4-wires) and two pressure head sensors systems[7] for an indirect velocity measurement. 24 temperature sensors were for this purpose installed in the earth in distances of 6m, 17,5m, 30m and 54m.

With 16 more sensors, at the same distances, the inner surface temperature of the concrete pipes is measured sideways and on the top. The remaining 8 sensors are room temperature sensors, which are mounted approximately 20 cm away from the inner concrete surface of the pipes into the air inlet flow.

These data are used to guide the actual status of the air earth heat exchanger with D/A-converter[8] via a bus system to a central process controller. With this, it is possible to store all data for detailed analysis and to give information on public displays for students and visitors.

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[4] DDC „direct digital control"
[5] PCU: „processor controlled unit"
[6] PT100: Platinum resistor temperature sensor, 0°C, 100,000 Ω increases each above 1°C approx.. 0,4 Ω
[7] up to now, there is no signal from this
[8] D/A-converter: converts analogue (electrical) in digital bits.

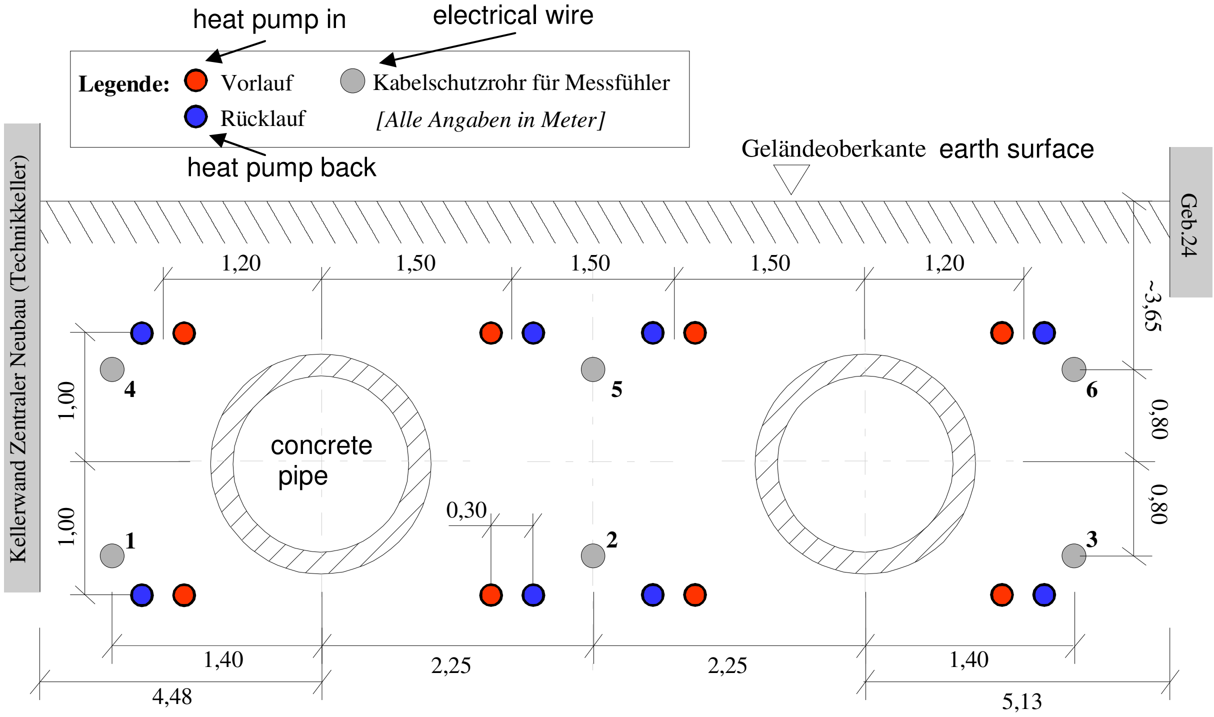

Figure 4: Positioning of the Concrete pipes and the Heat Pump Circuit Pipes (in meter)

4. Modelling of Earth-Heat-Exchanger

There exist as analytical as well as numerical methods of modelling to calculate such earth heat exchangers, but usually without the heat pump circuit.

Fundamental for all models is the Fourier differential equation

$$\frac{\partial T}{\partial t} = a \cdot \Delta \cdot T + \frac{\dot{W}}{c \cdot \rho} \qquad (4.1)$$

with
- α : Temperature Conductivity [m²/s]
- c : Specific Heat Capacity [J/(kgK)]
- T : Temperature [K]
- $\dot{W}$: Heat Power Density [W/m³]
- Δ : Laplace-Operator
- ρ : Media Density [kg/m³]

A useful analytical model is the geometry shape factor model described by K.J. Albers 1991 [2]. This method neglects the Fick's diffusion and Darcy streams, uses a simplified heat transfer equation and makes a superposition of temperature fields of the undisturbed earth (nonsteady) and the disturbed earth with the concrete pipes (steady).

The temperature curvature over the period of one year is given by a cosine function, which leads in the undisturbed earth to an exponentially damped temperature dependence on the deepness.
Earth temperature:

$$T_{E,undisturbed}(x,t) = T_m + (T_{max} - T_m) \cdot e^{-x \cdot \sqrt{\frac{\pi}{a \cdot t_0}}} \cdot \cos\left(2 \cdot \pi \cdot (\frac{t}{t_0}) - x \cdot \sqrt{\frac{\pi}{a \cdot t_0}}\right) \quad (4.2)$$

with x : Position under the Earth Surface [m]
t : Time [s]
a : Temperature Conductivity [m²/s]

Air temperature:

$$T_L = T_m + (T_{max} - T_m) \cdot \cos(2\pi \frac{t}{t_0} - \rho_0) \quad (4.3)$$

with T_m : Annually Averaged Air Temperature [°C]
T_{max} : Maximum Average Month Temperature [°C]
t_0 : Time Period, here one year [s]
t : Time [s]
ρ_0 : Phase Shift

For the temperature filed of the undisturbed earth, the following simplified equation is used

$$\nabla^2 T = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0 \quad (4.4)$$

which lead to an isothermal solution with a shape (geometry) factor S

$$\dot{Q} = \lambda \cdot S \cdot (T_1 - T_2) \,. \quad (4.5)$$

The final result is the superposition of an unsteady and a steady temperature field

$$T(x,y,t) = T_{E,stat}(x,y) + T_{E,instat.}(x,t) \quad (4.6)$$

In order to integrate inner heat sources like the heat pump pipes, Mr. Jörn Herz extended this shape factor model. For this purpose he made the assumption, with respect to an analytical solution, that the heat power density is alternatively independent or linearly dependent from the temperature.

This would be possible, because of the dependence of the enthalpy flux on the earth temperature, which is at the inlet higher than at the outlet, with respect to the higher temperature difference. For simplification, the temperature decrease between in- and outlet is considered to be linear with the pipe length.

Figure 5 shows the geometric conditions of the temperature and a comparison (upper picture) to the heating circuit in the earth with constant difference.

In a next step, the linear curvature (red) will be segmented in constant average values (green), in order to use the shape factor model mathematically in the usual way.

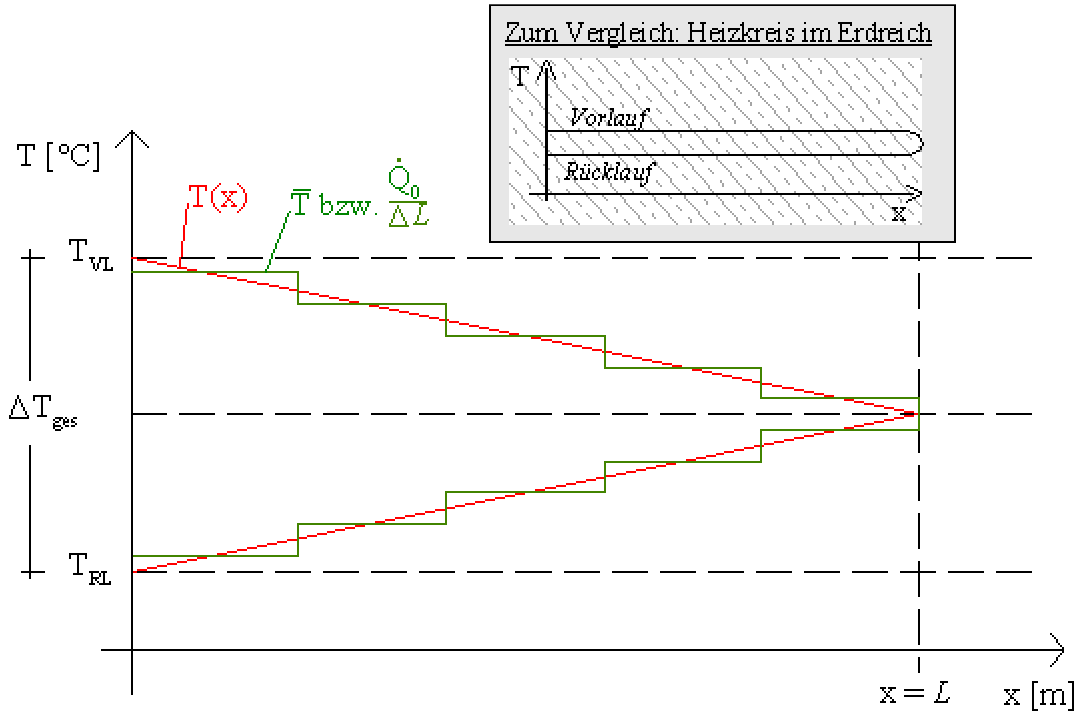

Figure 5: Linear Temperature Dependence between In- and Outlet of the Single Heat Circuits

Further, Mr. Herz dealt with the heating circuits a) as line shaped (one dimensional) heat sources and b) cylinder like heat sources (heat source and drain method), using the formulas

a)

$$T(r,t) = -\frac{\dot{Q}_0}{4 \cdot \pi \cdot \lambda \cdot L} \cdot Ei\left(\frac{-r^2}{4 \cdot a \cdot t}\right) \qquad (4.7)$$

with the exponential integral $Ei(-\zeta) = \int_{\zeta}^{\infty} \frac{e^{-u}}{u} du$

b)

$$T(r) = T_0 + \frac{\dot{Q}_0}{2 \cdot \pi \cdot \lambda \cdot L} \cdot \ln\left(\frac{r_0}{r}\right). \qquad (4.8)$$

The total temperature field of an earth pipe with the heat sources of the heat pump results as a superposition of all single calculated heat circuits with different segmented heat fluxes $\dot{Q}_i$ and the temperature field of the heat drains.

For further details and explanations and insight see the diploma thesis of Jörn Herz [1] and the dissertation thesis of J.K. Albers [2].

5. Measurements

All Measurements were done manually, because the automatic measurement system is already not completed.

Manual temperature measurements were done on

- the heated earth area
- the surfaces of the concrete pipes
- inner temperature of the concrete pipe (air flow)

with respect to the working status of the heat pump.

6. Results

The following graphics show same representative the temperature dependences as measured.

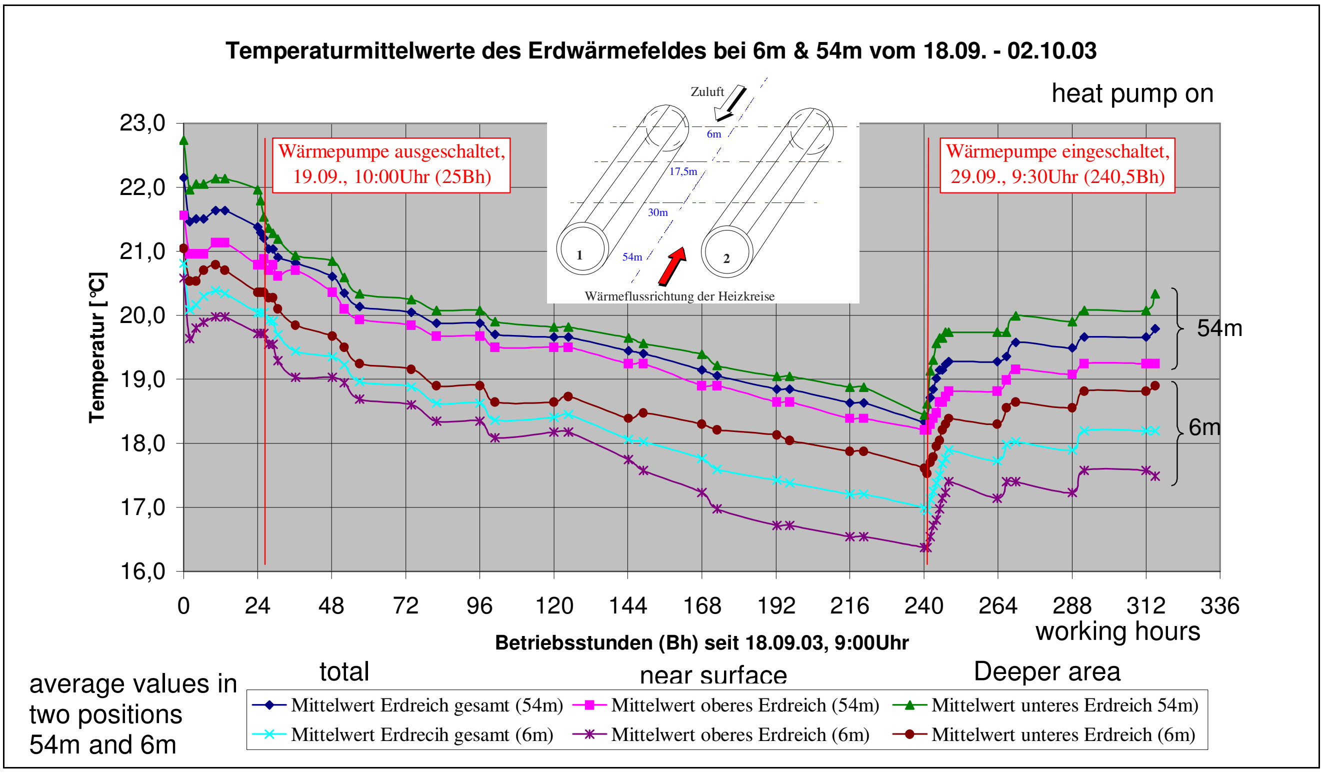

Figure 6: Averaged Temperatures of the Earth Field, without and with heat pump

The following figure 7 gives the time dependence of the earth heating process with the help of the heat pump in the same positions and with the average evaluation as in figure 6.

This diagram shows, that the heat pump recovery system is an effective method to save heat energy.

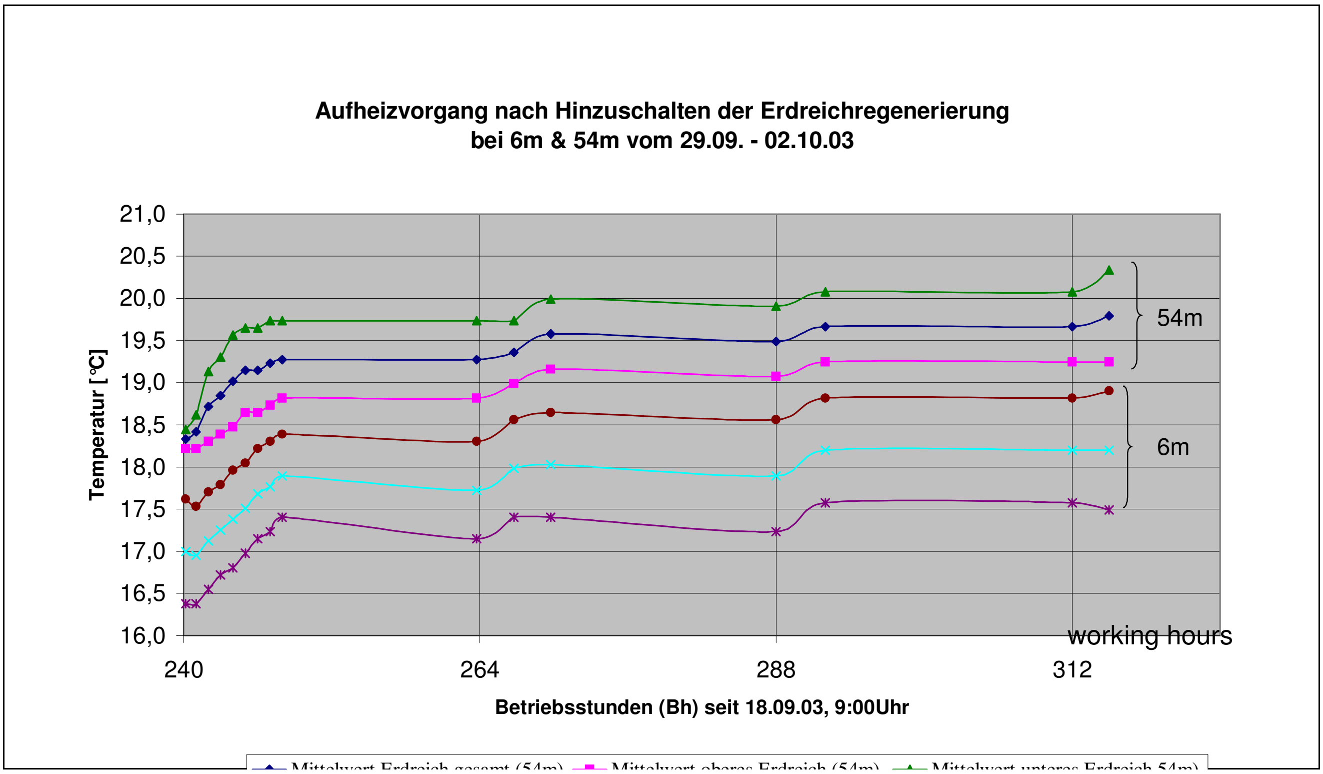

Figure 7: Heating process of the Earth field with the Heat Pump (legend see figure 6)

For more results of the done measurements see the diploma thesis of Jörn Herz. He correlates also concrete pipe temperatures, air temperatures from inlet and outlet, mixed working conditions and their time dependences etc. Even a heating and cooling power balance was made.

But this first diploma thesis on this installation at the Umwelt-Campus in Birkenfeld is only a fist step to a deeper understanding of such systems. An over all evaluation of the complete energy cycle, including electrical energy and efficiencies, are still to be done. The question to be answered is, how good is the total energy efficiency of this system compared to other possibilities. Therefore further project works and diploma thesis would follow.

7. Conclusion and Final Remark

The system technology of the earth heat exchanger combined to a heat recovery with heat pump was analysed experimentally and theoretically. The presented results are solid foundation for a detailed evaluation of this system concerning the total energy efficiency.

References

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[2] K. J. Albers*: Untersuchungen zur Auslegung von Erdwärmetauschern für die Konditionierung der Zuluft für Wohngebäude,* Dissertation an der Universität Dortmund, Abteilung Bauphysik, Dortmund 1991